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14. ABSTRACT The long-term goals of the research have been to investigate the important mechanisms involved in the interaction of current and waves with structures in the ocean. We have studied the ultra-high resolution controlled vibration of cylinders in a flow, and have been able to accurately predict free vibration response, as well as to understand free vibration phenomena, by employing "energy portrait" diagrams. We have constructed an accurate map of force and vortex modes in the plane of amplitude-wavelength, which relates well to the earlier Williamson-Roshko map of modes (1988). We discover new modes of vibration and vortex dynamics for a rising sphere, which are defined as the R, 2R and 4R modes, the latter comprising 4 vortex rings per cycle of its zig-zag trajectory. From a large set of very careful experiments involving rising and falling spheres, we have defined a new map of trajectories and vortex mode regimes, in the plane of mass ratio and Reynolds number. A significant discovery in this work, is the existence of a critical mass for unrestrained bodies. Our work has formed the basis of several comprehensive papers in *Journal of Fluid Mechanics, Proceedings of the Royal Society, Physics of Fluids, Journal of Fluids and Structures* and several other journals. The P.I. has chaired a series of international conferences on *Bluff Body Wakes & Vortex-Induced Vibrations* (the 6th one recently in Italy in 2010).

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GOALS AND OUTLINE

The long-term goals of the program have been the discovery and understanding of generic phenomena in a whole class of vortex-induced vibration systems. We have been studying the fundamental mechanisms involved in the interaction of ocean current with axisymmetric or cylindrical bodies, including both rigid and flexible structures, which are tethered or free (restrained or unrestrained) to respond to the fluid forcing. We have been investigating the in-line and transverse dynamics and forces, wake vortical motions, and signatures of such bodies undergoing vortex-induced vibrations (VIV).

We have recently completed a study which compares predictions based on (extremely high resolution) controlled vibration, versus measurements from free vibration. We have employed these results to understand forcing and vortex dynamics responsible for fundamental free vibration phenomena. Also, of strong interest has been the study of freely rising and falling bodies. For the period 2007-2011, we have placed an emphasis on an understanding of some of the effects of Reynolds number in our research. We have had a central goal over the last year to extensively publish our new material in refereed journals.

This award has been used to support a number of students at different periods of their study, and has been instrumental in training them in their PhD programs. The award has been very effective in providing a cohesive research group with sufficient critical mass to move rapidly forward in the research program. The award has been used to support wholly or in part a large number of research publications which are listed at the end of this Final Report.

Our major emphasis with this work has been the combined study on a number of diverse vortex-induced vibration problems, with a major goal of discovering universal characteristics of such systems. We have completed a large set of studies, some of which are published in *Journal of Fluid Mechanics, Proceedings of the Royal Society, Physics of Fluids, Journal of Computational Physics, Physical Review Letters* and *Journal of Fluids and Structures*, amongst other journals, and are listed in the Publications section later.

The support of the Ocean Engineering Area of the Office of Naval Research for both our research, and that of other groups, has directly led to significant steps forward in this field, and the field has progressed far beyond our understanding of one decade ago, mostly encouraged by new

techniques in computation and experiment, and also from the study of much lower mass and damping than were hitherto studied. Some of the earlier results are discussed by the PI comprehensively in an invited review paper, "Vortex-Induced Vibrations" (Williamson & Govardhan, 2004 volume of *Annual Review of Fluid Mechanics*). We should mention also that this has been followed by a number of invited plenary presentations on the work done in this award period, and the recent presentation of the "Wallace" Prize lecture at MIT (28 Oct 2011).

OBJECTIVES

Over the period 2007-2011, the objectives of this program have developed - projects have yielded many new publications and submissions, and we have shifted our focus as newer projects evolved in the research program. As a general area of research, we have investigated the response and forcing on elastically mounted rigid and flexible bodies (cylinders) in a current, with increased emphasis recently on the effects of Reynolds number. A primary interest has been to understand resonance phenomena and the relation between forcing and wake-vortex dynamics. A second area of research, which has again moved forward substantially, over the grant period, involves the rising and falling of bodies, since this has a fundamental connection with phenomena concerning elastically mounted structures. Another objective has been the use of very high resolution controlled vibration force data, to predict free vibration response, but also to understand clearly why certain phenomena occur in steady state (and transient) free vibration. Other components of the research have been the study of tethered body dynamics; and the vortex-induced vibration of bodies which have a spanwise variation of amplitude. Finally, our overall objective, which has been the most significant in our research program, is to uncover generic phenomena for a whole class of VIV systems.

APPROACH OF THE RESEARCH

Our approach over the period 2007-2011, has been primarily experimental in nature, but has involved analysis. We have been using our facility, the Cornell-ONR Water Channel, for VIV experiments, and it has enabled extremely high-resolution controlled vibration studies. We have been using successfully a pair of vertical water tanks, where we can investigate the dynamics of different bodies of interest as they rise or fall through the fluid, as this problem is directly allied to flow-induced vibration, under conditions of very low damping.

The challenges in this research have been in achieving sufficient resolution temporally and spatially to measure vorticity and flow structure. Stimulated by these challenges, we have been able to monitor precisely the dynamics of such bodies, and then we have employed (during 2007-10) the computer-controlled XYθ Towing Tank to impart *identical scaled motions* for larger-scale bodies (matching Reynolds numbers) to more readily measure forces and vorticity dynamics.

A new area of research has evolved from the above, and comprises a combined *cyber-physical* approach to fluid-structure interactions - one where the equations of motion are satisfied both in physical space and in software. This line of research has a huge potential to contribute to new studies, otherwise impossible in a laboratory.

Effective diagnostic techniques include DPIV (Digital Particle-Image Velocimetry), force measurements (using now three force balances), and LIF (Laser-Induced Fluorescence) visualisation. Individuals comprise a team of both undergraduate and graduate researchers, working vigorously with the P.I. on these projects.

OVERVIEW OF RESEARCH ON THIS AWARD

We have made substantial progress on these projects funded by the ONR, leading to some new discoveries, and to a large number of refereed journal publications (please see Publications List). In the period of this award, we have explored the rich phenomena for VIV of cylinders and other bodies, at extremely low mass and damping. Our series of experiments has enabled us to make some fundamental new discoveries concerning vortex-induced vibration.

We have also made some collaborations (Oxford University and Marseille) on topics of interest to this line of research. We have also embarked on a fertile line of research involving vortex dynamics from an analytical approach, and have discovered a method to determine stability of vortex flows, using an idea generated initially by Lord Kelvin in 1875, and we employ what we have called the "Imperfect Velocity Impulse" (IVI) Diagrams. For this work my PhD student Paolo Luzzatto-Fegiz has been awarded 5 fellowships (including three years at Cambridge University), and a national prize for his PhD called the Acrivos Prize, with an associated plenary presentation at this year's APS Meeting (Baltimore, Nov 2011).

Concerning generic phenomena, and relevant to some of the results in this report, we have been able to show that, for all VIV system geometries we have investigated, there exists a critical mass, when there is a catastrophic jump in the response of the system to vortex-induced forces. Further to this, we show that the critical mass should be a feature of all such VIV systems, governed approximately by the same type of equations of motion, and is therefore a generic phenomenon in VIV systems. We have measured the critical mass for several VIV systems (Govardhan & Williamson, 2005, *Journal of Fluid Mechanics*; Flemming & Williamson, 2005, *Journal of Fluid Mechanics*; Jauvtis & Williamson, 2004, *Journal of Fluid Mechanics*) and for all the physically distinct cases so far, it seems to be close to 0.5 - 0.6. The underlying reason for the coincidence of values is a challenging question which remains unanswered presently, and it is of significance to understand, since it has such a practical impact for VIV systems.

Much of the thrust this past year has been to complete several lines of work and publish the results in refereed journals. Our contributions also include reviews and book chapters, either past or in preparation, on the research carried out under this program. We mention below several publications which have now appeared in a number of refereed journals.

One part of our research was to study effects of Reynolds number on VIV. Part of this line of work involves our recent publication concerning the peak-amplitude Griffin plot (Govardhan & Williamson, 2006, *Journal of Fluid Mechanics*) as a solid base. More recently in 2007-2010, we have found how the values of the critical mass (below which there is an unlimited regime of velocities for resonance) depend on Reynolds number, which was published as Morse & Williamson (2009), *Physics of Fluids*, **21**, 045105.

In our studies on sphere dynamics too, we have determined the influence of both mass ratio (relative density) and Reynolds number (Re), over a wide range of Re, creating a new accurate map of dynamics and mode regimes, as well as fundamental force measurements (see later figures 2 and 3) This has now appeared in Horowitz & Williamson, *Journal of Fluid Mechanics* (2010), **651**, 251-294, coupled with the front cover of that journal. A related piece of research concerning rising and falling cylinders, completed in 2009, has led to a recently published paper for *Journal of Fluid Mechanics* (2010), **662**, 352-383. This is mentioned briefly later.

Other completed research over the period 2007-2010 has employed a computer-controlled lead-screw carriage system imparting transverse motion to a cylinder in a flow, exploring an extremely high resolution data set in an extensive regime of the amplitude-frequency plane, keeping the Reynolds number fixed. This study has revealed key new understandings concerning what happens in free vibration. This has led to a publication concerning steady state free vibration in Morse & Williamson (2009), *Journal of Fluid Mechanics,* **634**, 5-39, and has more recently been followed by a paper concerning transient vibration predictions, Morse & Williamson (2010), *Journal of Fluid Mechanics,* **649**, 429-451.

Further related completed work comprises a book chapter on "Flow-Structure Interactions" for *Handbook of Environmental Fluid Dynamics* (2012), and a paper on forces on bodies in wave flows (2009) *Proceedings Royal Society,* **465**. We have edited and published a complete volume of *Journal of Fluids and Structures* (2009) comprising selected papers from our own conference *BBVIV-5* in Brazil (2007). This has been followed by another complete volume, comprising papers from our conference BBVIV-6 held in Capri Island, Italy in June 2010; *Journal of Fluids and Structures* (2011), Volume **27**, 247 pages.

Several papers to *Journal of Fluid Mechanics* and *Proceedings Royal Society* have either been published in 2009-2010 or submitted, in the related area of vortex dynamics and stability, including wake flows (*BBVIV-6* Conference), by Luzzatto Fegiz and Williamson, comprising also a paper just appeared in (2010) *Physical Review Letters,* **104**, 044504, and a paper by Mackowski & Williamson, *Journal of Fluids and Structures* (2011) **27**, 748-757.

SELECTED NEW RESULTS FROM THIS RESEARCH PROGRAM

The research on this grant has led to a large number of publications which are listed at the end of this Final report. Some of the results have been selected and are expanded upon here.

Over the period 2007-2011, further research has been completed to study the rich set of VIV phenomena for bodies at extremely low mass and damping. The research has enabled us to make some fundamental new discoveries concerning vortex-induced vibration, which have been published or await publication.

- We have been exploring a wider regime of Reynolds numbers, and its effect upon the character of VIV response and "critical mass".
- The effect of Reynolds number is also key to the exploration of rising and falling bodies which have a close correspondence with phenomena for elastically-mounted bodies.
- We have further studied very high resolution controlled vibrations, which has, we believe, yielded a deeper understanding of phenomena for freely vibrating bodies. Selected results from these studies will be described below.

For all VIV system geometries we have investigated, there exists a critical mass, when there is a catastrophic jump in the response of the system to vortex-induced forces. *We show that the critical mass should be a generic feature of all such VIV systems.* We have also recently looked into the effect of Reynolds number on the critical mass for the vibrating cylinder. One must expect that there will be some variation in this value as Reynolds number is varied. However, even over a regime Re = 1,000 - 30,000 the critical mass varies only from 0.36 - 0.54 (Morse & Williamson, *Physics of Fluids* (2009), see Figure 1.
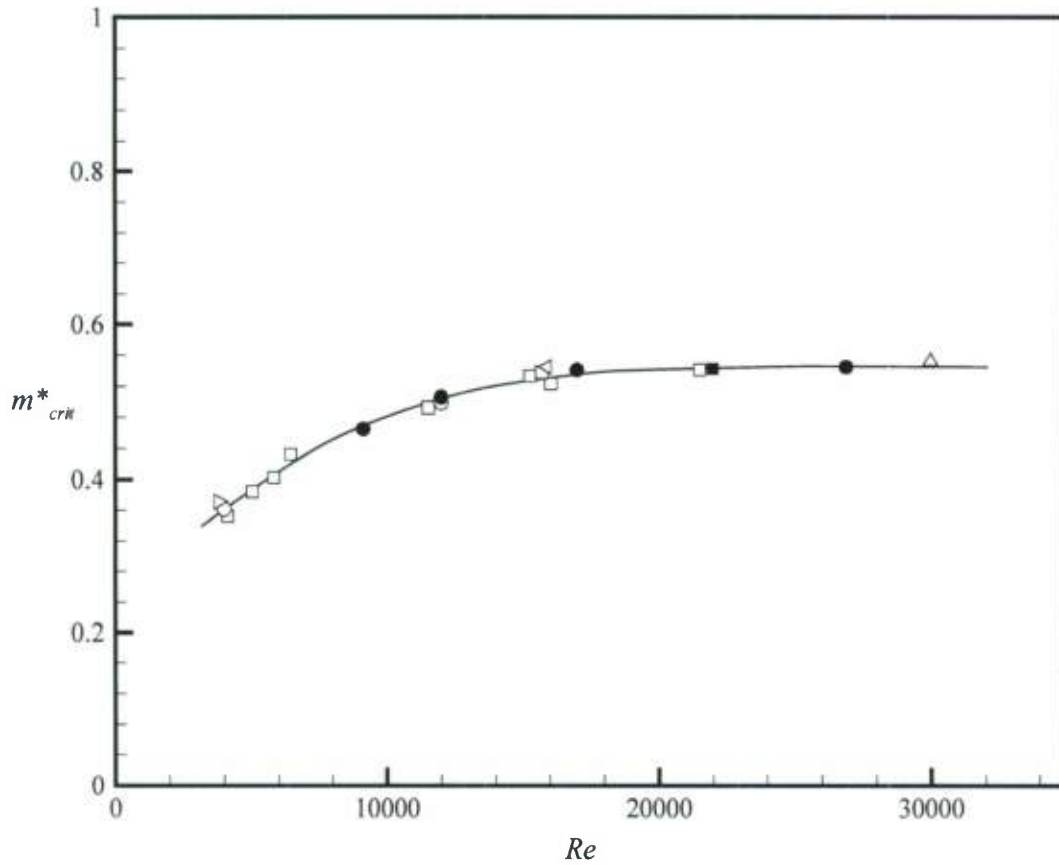
Figure 1. Critical mass as a function of Re. Values of m^*_{crit} are obtained from experiments at infinite normalized velocity: present results; Govardhan & Williamson (2002); Govardhan & Williamson (2000); Hover, Tvedt & Triantafyllou (2001); Brankovic & Bearman (2006); Hover, Techet & Triantafyllou (1998)

Over 2007-2011, we turned our attention to the case of rising and falling spheres. This problem was first studied by Newton in 1726, who charmingly investigated the flight of hog's bladders, and since then the conditions under which a sphere will vibrate were still not clear for almost 200 years. The status up till recently is indicated by the scatter of the data points showing vibration (either periodic or chaotic), or no vibration, in Figure 2(a).

Referring to Figure 2(a), all previous studies conclude that all rising spheres (m*<1) vibrate either periodically or chaotically. Our new results now show that there exists a typical critical relative density between 36%, and 61%, corresponding well with the elastically mounted bodies. *In other words, there exists a significant regime where rising spheres do not vibrate.* These regimes of vortex dynamics are shown in Figure 2(b). We exhibit the new map of regimes for a rising and falling sphere in Figure 4, where we indicate the predominant mode of vibrations also. These new regimes of vortex dynamics are from Horowitz & Williamson (2010) *Journal of Fluid Mechanics* (2010), , **651**, 251-294.
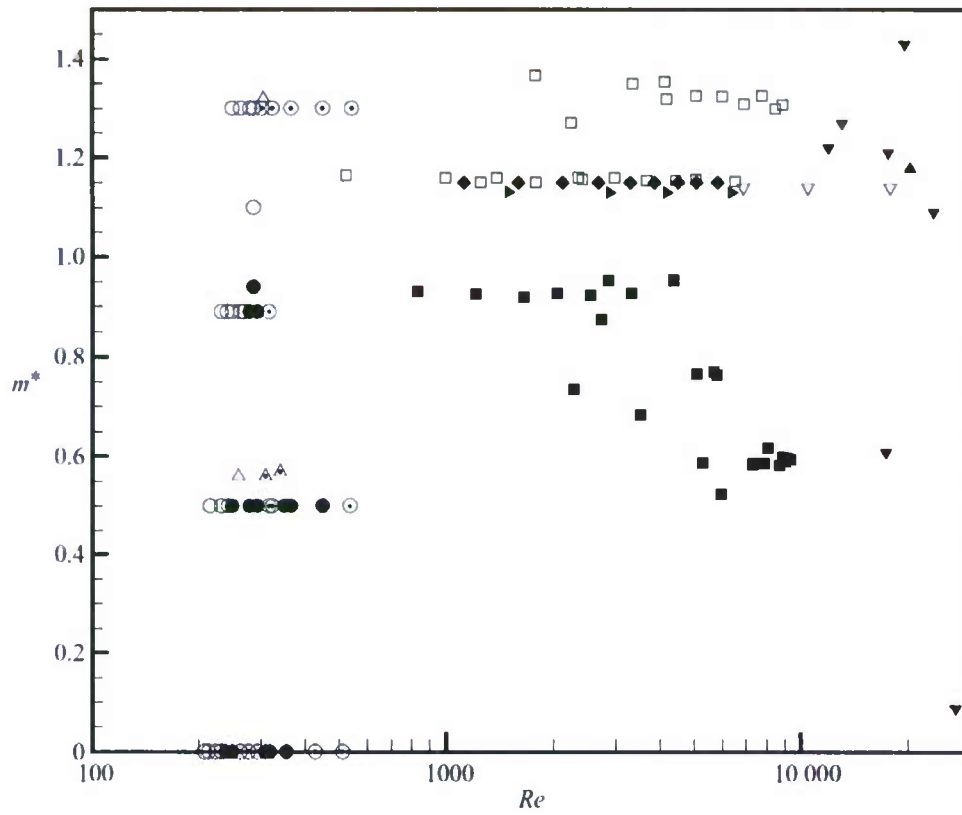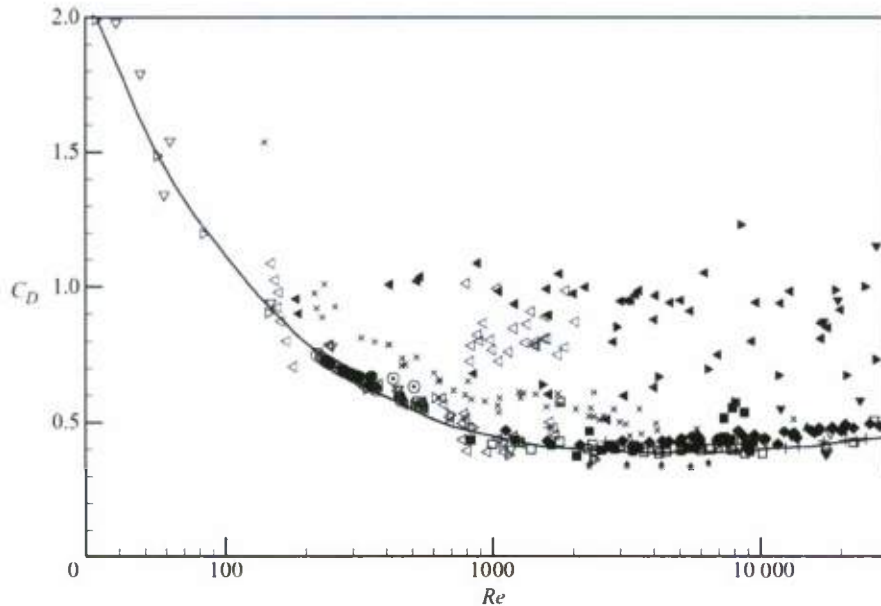
FIGURE 2(a): Regimes of motion found in previous studies of freely rising and falling spheres, mapped in the {m*, Re} plane. Solid symbols indicate vibration, open symbols indicate rectilinear motion, and bullseye symbols indicate 'chaotic' motion.
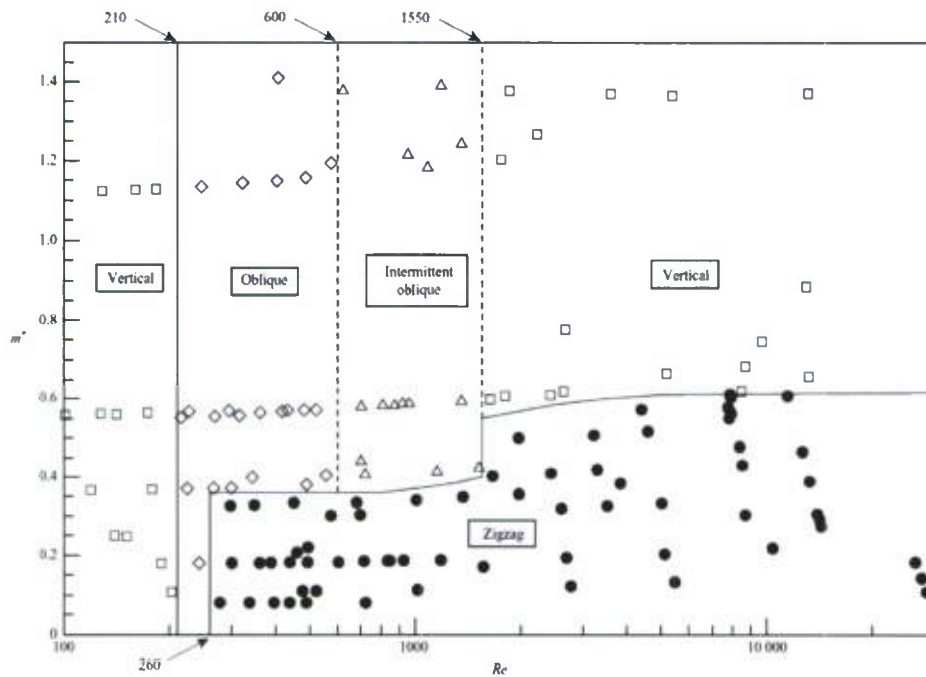

FIGURE 2(b): New Map of regimes of sphere motion in the {m*, Re} plane, following 168 separate runs, from Horowitz & Williamson (2010) *Journal of Fluid Mechanics*.

This research has also enabled us to tie down the drag coefficient as a function of Reynolds number, in Figures 3(a) and 3(b). It is evident that there existed quite a large degree of scatter in the drag coefficient, much of it due to the existence or non-existence of vibration in the sphere's trajectory, which in turn is related to the relative density of the body, and also to the care in taking into account background turbulent motions in the ambient fluid of the laboratory. By suitable care in such experimental conditions, the drag approximately falls onto two distinct curves, one for the zig-zag trajectory, and the other for rectilinear trajectories, as shown in Figure 3(b).

FIGURE 3(a): Scattered mean drag coefficients from previous studies of rising and falling spheres. Solid symbols indicate vibration; open symbols indicate rectilinear; bulls-eye symbols indicate 'chaotic' motion.; —, drag of stationary sphere compiled the book by Schlichting (1955), using data from Wieselsberger (1921) and Liebster (1927).
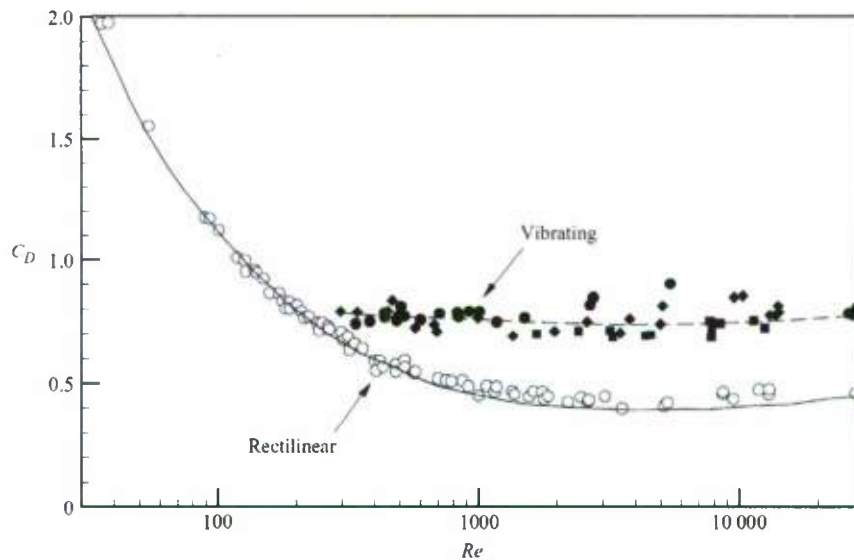
FIGURE 3(b): Mean drag coefficient for rising and falling spheres, lying clearly along two distinct curves. The drag for spheres moving rectilinearly is approximately equal to the stationary sphere drag. Vibration causes a significant increase in drag. This effect could actually be deduced from Newton's observations of falling hog bladders in 1726! From Horowitz & Williamson (2009) *Journal of Fluid Mechanics* (2009):
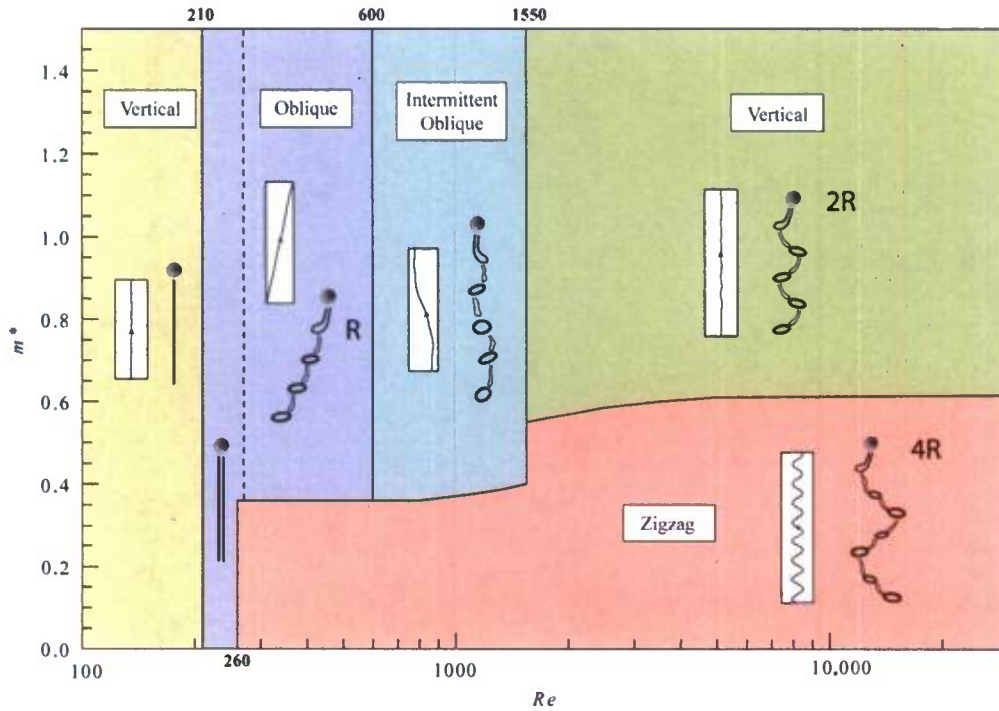
Figure 4. Map of regimes of sphere motion and associated wake patterns in the {*m**, *Re*} plane. Typical trajectories are shown for each regime.

Laser-Induced-fluorescence (LIF) visualisations exhibiting the 4-vortex ring mode, as in Figure 5, are quite unlike any vortex mode that develops behind fixed spheres, and this new result has appeared in Horowitz & Williamson (2009) *Physics of Fluids*.
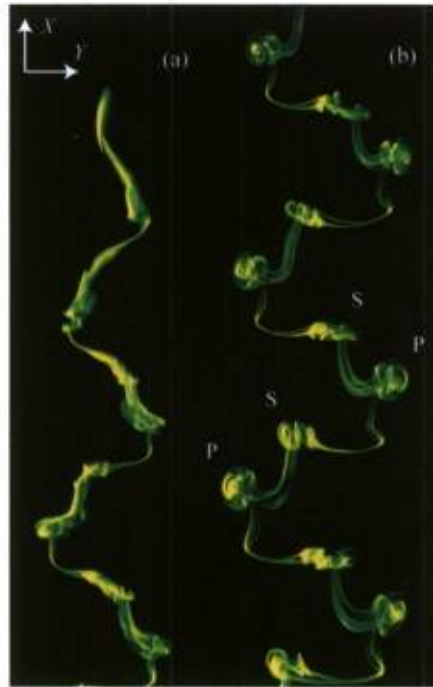

Figure 5. A new mode of vortex formation for a vibrating sphere comprising four vortex rings shed per cycle of oscillation. The primary structures are labelled 'P' and the secondary structures are labelled 'S' for one complete cycle of oscillation. The sphere, located at the top of (a), has risen out of the frame in (b), taken approximately three periods ($t/T = 3$) later. $m^* = 0.08, Re = 450$.

In summary, much of the difference in previous studies seems to be related to disturbed background motions of the surrounding fluid, which would trigger vibration, when otherwise it would rise rectilinearly. Observations of helical trajectories seems also to be related to background turbulence in the surrounding fluid, rather than intrinsic to the flow. Light spheres undergo large amplitude zig-zag motion, confined to single plane.

Over the period 2007-10, we discovered a new *4R mode of vortex dynamics comprising four vortex rings* formed in each cycle of the body's zig-zag vibration, quite unlike any vortex mode that develops behind fixed spheres (see Figure 3). This new result has just been published in Horowitz & Williamson (2010) *Journal of Fluid Mechanics*. (2010) **651**, 251-294. We display here, in Figure 6, the structure of the 4R mode, using combined visualization and PIV measurements of vorticity.
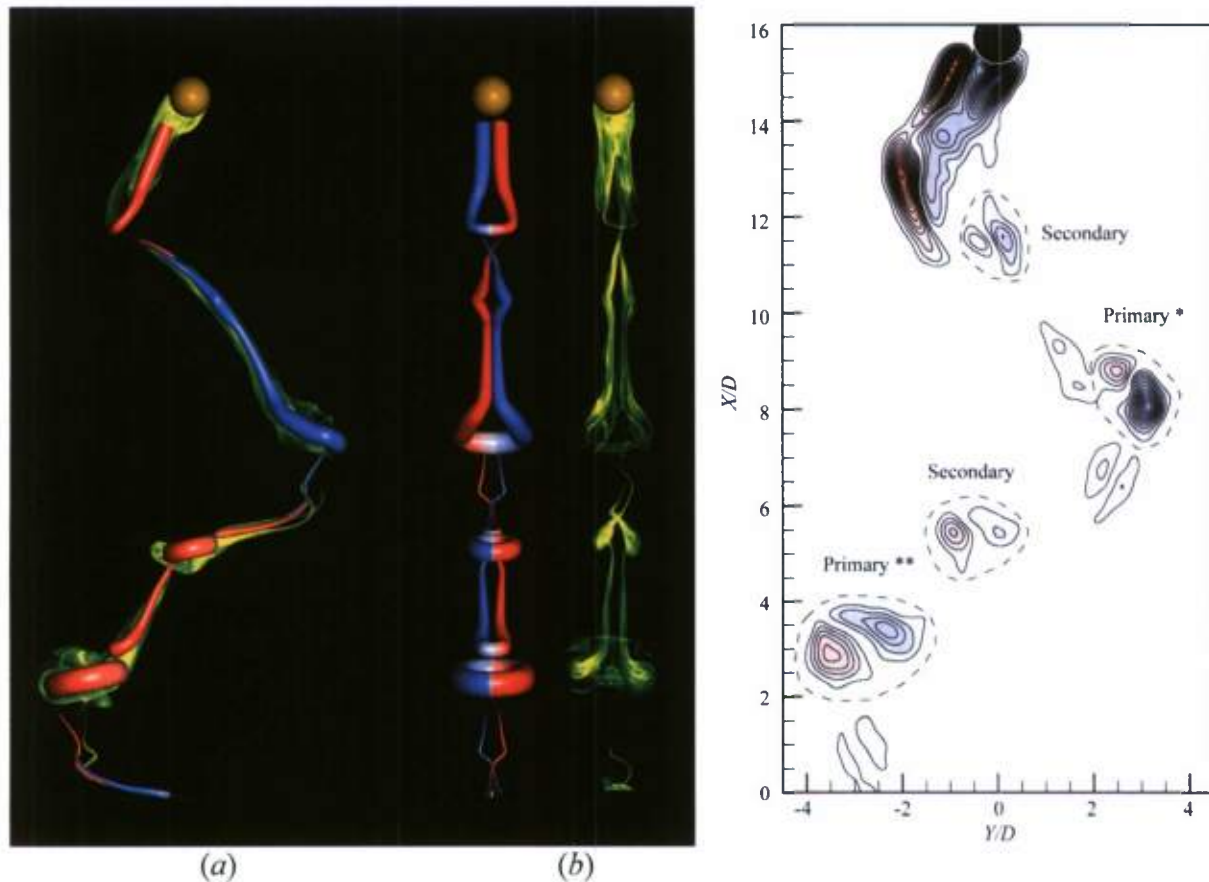

FIGURE 6: Creation of a three-dimensional rendering of the 4R mode. The positioning of the streamwise vorticity structures is determined from the dye visualizations. The location and size of the vortex rings are based on data from PIV measurements. The colour corresponds to the initial sign of the streamwise vorticity component. On the right: Cross-sectional vorticity measurements of the four-ring 4R wake pattern.

During 2007-10, we completed a further study on the dynamics of unrestrained cylinders rising or falling through a fluid. This is a vortex-induced vibration (VIV) system comprising both transverse (Y) and streamwise (X) degrees of freedom, but without any restoring force. This problem represents a limiting case among studies in VIV, and extends some other recent research of elastically-mounted bodies having very low spring stiffness, as well as very low mass and damping. When the mass ratio is reduced below a certain critical value, $m^*_{crit} = 0.545$, the cylinder suddenly

begins to vibrate vigorously and periodically with an amplitude of nearly a diameter ($A_Y* = 1$), and a streamwise oscillation of around $A_X* = 0.3$.

The periodic streamwise oscillation of the freely rising body has a phase relative to the transverse motion that is opposite to the values previously observed for elastically mounted two degree-of-freedom (*XY*) cylinders (Govardhan & Williamson, *Journal of Fluid Mechanics*, 2002). These unusual dynamics suggest that the motion of the rising cylinder may be characteristic of a new branch of response found only for very low mass ratios. From vorticity measurements, we find that when the rising cylinder vibrates periodically, it exhibits a 2P mode of vortex formation, the same mode that is found for elastically-mounted bodies in the absence of streamwise motion - this is shown in Figure 7. By considering the equations of motion, one major deduction mentioned in our last report is that *the rising cylinder is completely equivalent to a 2-degree-of freedom elastically-mounted system* where we have zero damping, and where the springs are removed, such that we are effectively considering very large normalised velocity U*. These experiments thus determine accurately the critical mass for an equivalent 2 degree-of-freedom elastic system. Further results are included within the paper Horowitz & Williamson, *Journal of Fluid Mechanics* (2010), **662**.
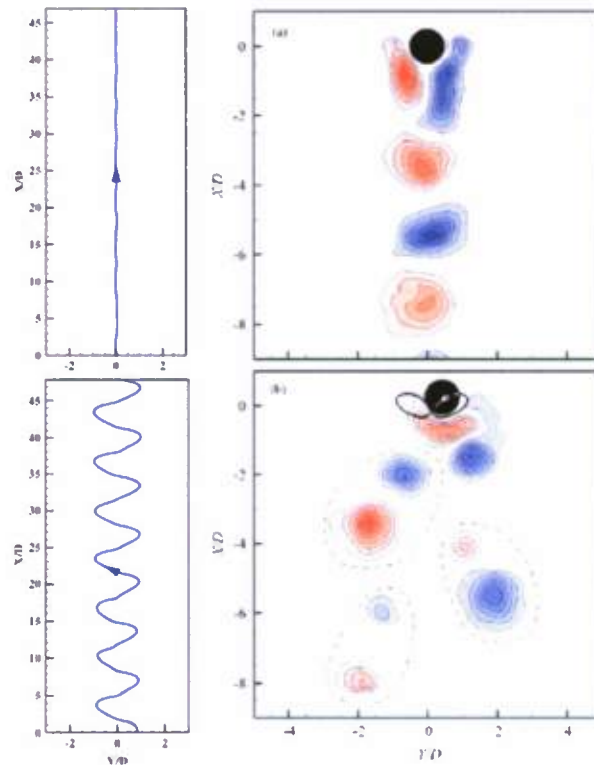
Figure 7. Trajectories above and below the critical relative density for rising cylinders, as well as vorticity measurements exhibiting the 2S and 2P vortex formation modes. (a) m* = 0.78. (b) m* = 0.45.

In 2008, we have been vigorously pursuing our study of controlled vibrations where we have first demanded of our system an *extremely high resolution* in the variation of amplitude and frequency of vibration. This is over a factor of 10 greater resolution than used previously. (Our cylinder was suspended vertically in a water channel, and oscillated sinusoidally transverse to a free stream, at a fixed Reynolds number). For each of our Reynolds numbers, a total of almost 6,000 runs were conducted! This is only possible in a continuously flowing (ONR-Cornell) water channel facility and thus could be automated and run unattended for days. Some idea of the extreme high resolution is given by our grid of data points in Figure 8.

Staubli (1983) - 280 runs   Hover et al. (1998) - 306 runs   Present study - 5680 runs
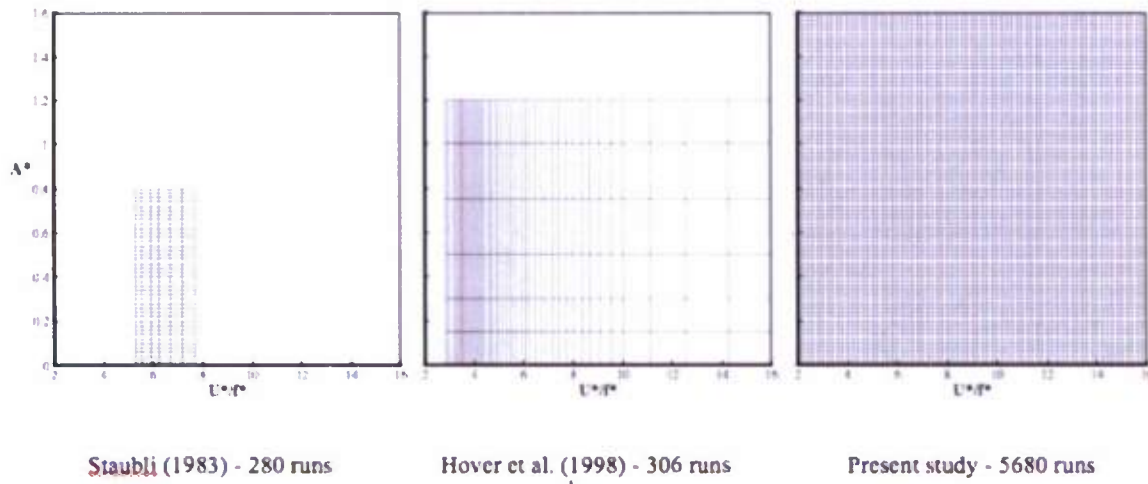
Figure 8. Extremely high grid resolution for our experiments in the amplitude-frequency plane.

A second principal point in these experiments is our essential need to *very carefully match the amplitude, frequency, and Reynolds number of the controlled system with elastically mounted cylinder system.* Some measure of the agreement between predictions from controlled vibration data and directly measured free vibration response is given in Figure 9. While the agreement is not perfect, it is indeed very close, and serves to illustrate the fact that despite the fact that free vibration displacement is not perfectly sinusoidal, controlled sinusoidal vibration experiments, where accurate and high resolution force measurements are compiled, are remarkably effective in prediction of vortex-induced vibration.

A key to this study is the compilation of high resolution contour plots of fluid force, in the plane of normalized amplitude and wavelength. With such resolution, we are able to discover discontinuities in the force and phase contours, which enable us to clearly identify boundaries separating different fluid forcing regimes. These appear remarkably similar to boundaries separating different vortex formation modes in the Williamson & Roshko (1988) map of regimes. A colour map of these different fluid force regimes is seen in Figure 10. Vorticity measurements exhibit the 2S, 2P, and P+S vortex modes, as well as a regime where the vortex formation is not synchronized with the body vibration. By employing such fine resolution data, we discover a high-amplitude regime where two vortex formation modes overlap..
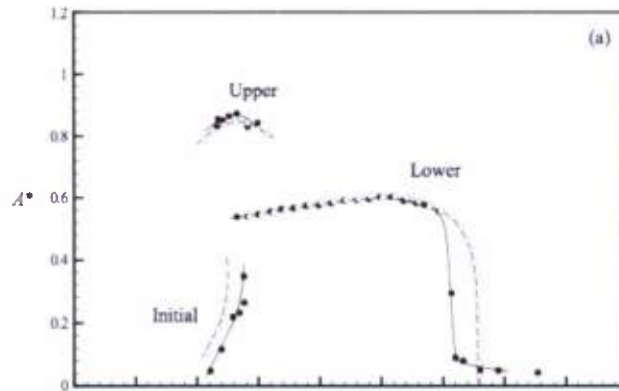
FIGURE 9. Measured and predicted amplitude response for a free vibration system at low mass-damping, $(m^*+C_A)\zeta = 0$. Open symbols - measured free vibration); Closed symbols - predicted response. $m^* = 10.49$. Re = 4,000 for the controlled vibration case; Re = 4,000 at peak amplitude for the free vibration case.
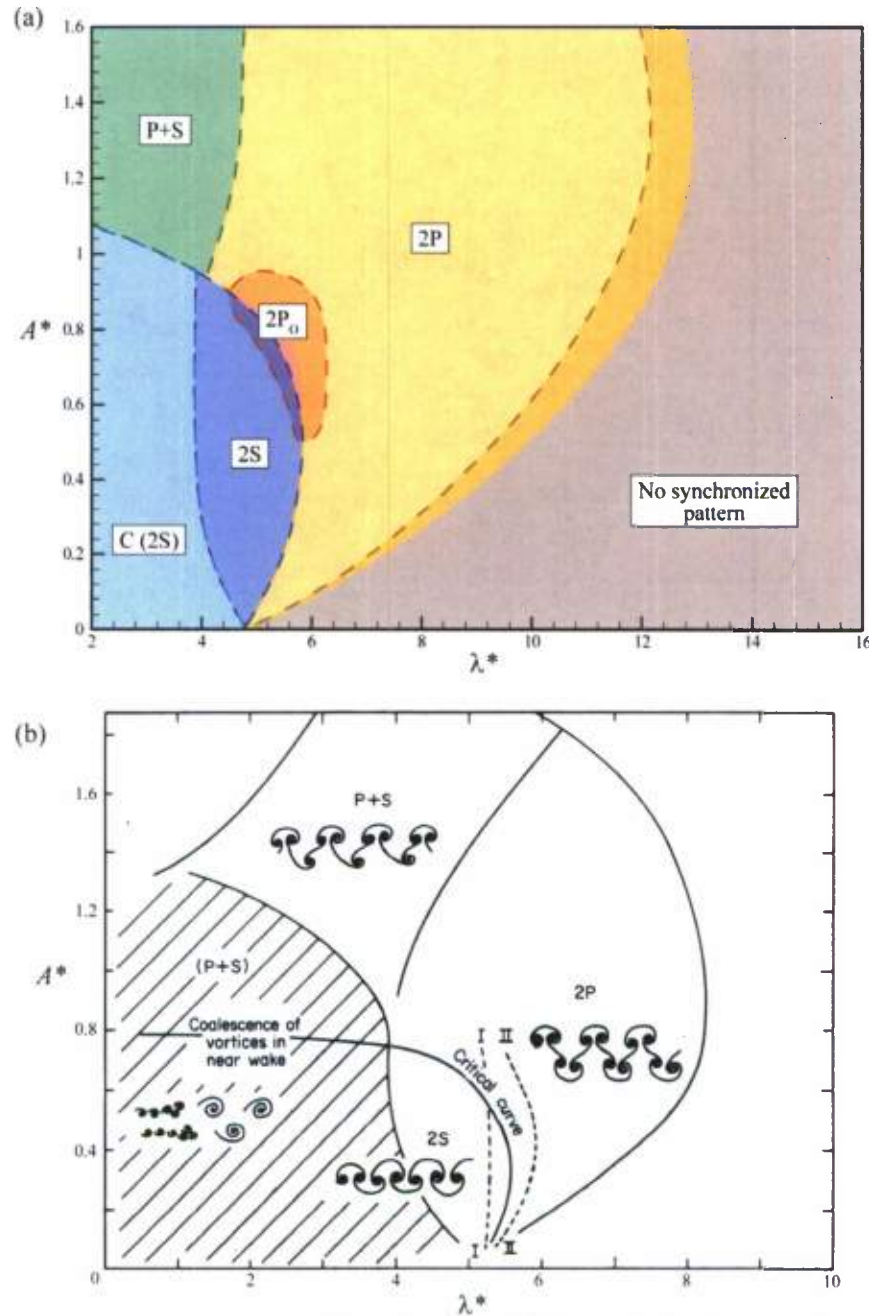
FIGURE 10. Map of vortex shedding regimes. There is a remarkable similarity between the mode boundaries we identify in the present study from force measurements in (a) and the boundaries identified by Williamson & Roshko (1988) from flow visualization in (b). Overlapping colors indicate regions where two vortex shedding modes overlap.

As mentioned above, vortex formation modes are found from vorticity measurements, exhibiting the 2S, 2P, and P+S vortex modes, as well as a regime where the vortex formation is not synchronized with the body vibration. By employing such fine resolution data, we discover a high-amplitude regime where two vortex formation modes overlap. This is termed the 2Po vortex formation mode, and is shown in Figure 11. This work has recently been published in *Journal of Fluid Mechanics* (Morse & Williamson, 2009). This paper was selected by the Journal as the *Focus on Fluids* paper for that month. A paper by Peter Bearman (2009, JFM) was written, focussing on our contribution.
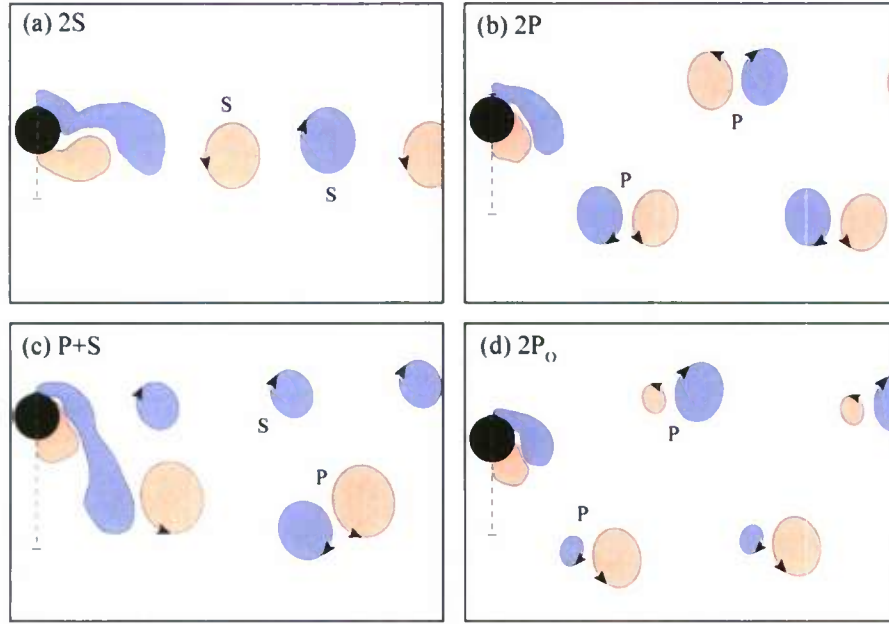
FIGURE 11: Representation of each of the main vortex formation modes, controlled vibration: {2S, 2P, P+S, 2P$_O$}. These were used in a paper by Bearman (2009) which focussed on our paper Morse & Williamson (2009) *Journal of Fluid Mechanics.* **The latter paper had been selected as the** *Focus on Fluids* **paper for that month by JFM.**

In 2008-10, we have introduced the concept of an "energy portrait" into our studies of vortex-induced vibration. This is essentially a plot of the energy of excitation (E^*_{IN}), and the energy dissipated to structural damping (E^*_{OUT}), as a function of amplitude (A^*), while keeping normalized velocity (U^*) fixed, as shown in Figure 12. We use these energy portraits to indicate the stability of equilibrium amplitude solutions, and to understand the mode transitions that occur between branches in free vibration. To demonstrate the usefulness of the concept of the energy portraits, we exhibit three examples. First, we note that the energy lost due to damping, E^*_{OUT}, will intersect the origin, and have a slope proportional to the specific value of mass-damping (m*+C$_A$)ζ. We also note that steady state response solutions are found where the energy into the system equals the energy out of the system.

In Figure 12(A), we show the case where the excitation energy curve intersects the energy dissipated line at only one point; this point is stable. On the other hand, in Figure 7(B), we have the situation where there are three equilibrium solutions, *but actually only the upper and lower solutions are stable* - the solution at intermediate amplitude is unstable. Such a case indicates hysteresis, which is actually what happens in free vibration. Stability and instability of equilibrium solutions in the energy portrait can be defined by the slope of the energy curves, at the equilibrium points, as follows:

$$\text{Stable:} \quad dE^*/dA^* < 0$$

$$\text{Unstable:} \quad dE^*/dA^* > 0$$

where E* is the net energy transfer into body motion; $E^* = E^*_{IN} - E^*_{OUT}$. In Figure 7(C), we exhibit one example, which predicts the intermittent switching that is actually observed in free vibration. See Morse & Williamson papers (2009-10) *Journal of Fluid Mechanics*.
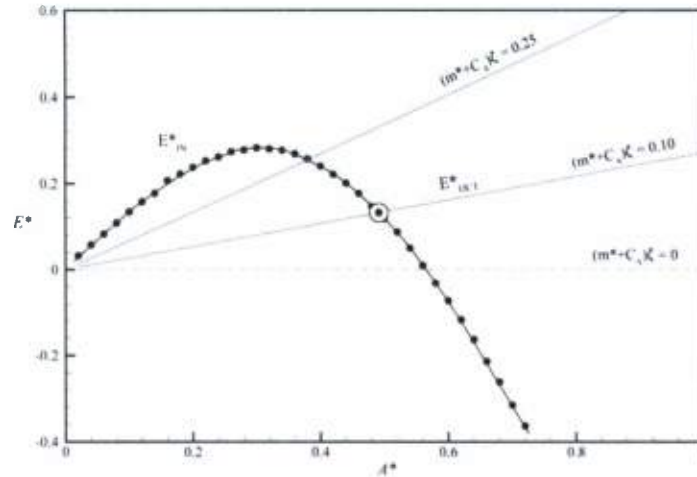
Figure 12(A). Energy portrait for $m^* = 10$, $U^* = 7.0$ (lower branch). The amplitude of the equilibrium point (marked by a bull's eye) decreases as the mass-damping increases.
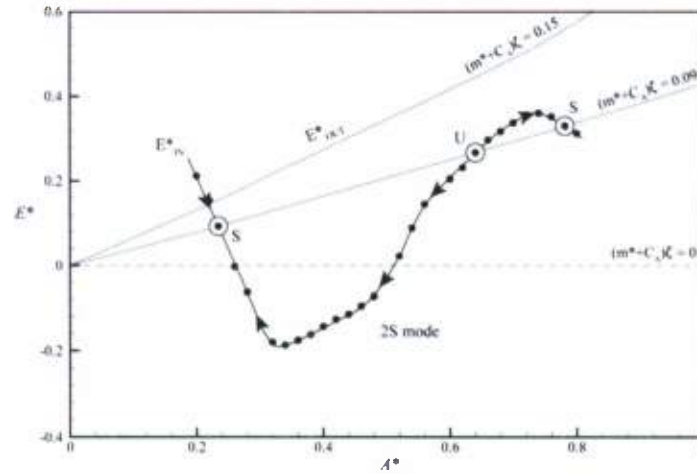

Figure 12(B). Energy portrait for $m^* = 10$, $U^* = 5.1$ (initial and upper branch). For low values of mass-damping there are two stable equilibrium points (indicated by `S') and one unstable equilibrium point (indicated by `U'). The stable equilibria correspond to the initial branch and upper branch of a free vibration response.
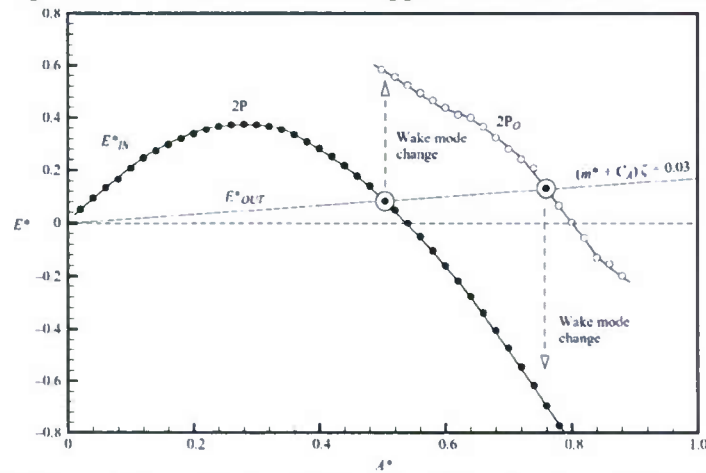
FIGURE 12(C): New prediction of intermittent switching of modes. Energy portrait for $m^* = 10$, $U^* = 6.3$ (upper and lower branches), showing distinct values of the fluid excitation (E^*_{IN}) for the 2P ($\bullet$) and $2P_O$ ($\bigcirc$) vortex-formation modes. Stable equilibria ($\odot$) exist for each vortex-formation mode, corresponding to the upper branch ($2P_O$) and lower branch (2P). A switch in the mode causes a jump in the fluid excitation and therefore a change in amplitude.

Not only do the energy portraits exhibit interesting phenomena, such as hysteresis, intermittent switching, but they also indicate where regimes of stable solutions exist in the plane of amplitude-wavelength. *We note carefully that, not only the fluid excitation must be positive, but also the amplitude solutions must be stable*, for free vibration to be predicted.

Over the period 2007-10, we have conducted further studies in our research program, collaborating internationally, leading to a published paper with Prof Paul Taylor and Alistair Borthwick (Oxford University) on the subject of structural forces due to a flow past cylindrical bodies within a focussed (extreme) wave group (Stallard, Taylor, Williamson, Borthwick, 2009, *Proceedings of the Royal Society*).

Our work has been presented at several major conferences, and has formed the basis of papers in *Journal of Fluid Mechanics, Proceedings of the Royal Society, Physics of Fluids, Journal of Computational Physics, Physical Review Letters* and *Journal of Fluids and Structures*, amongst other journals, and are listed in the Publications section later.

Invited presentations and conference seminars have been presented, and the PI has been Co-Chairman (and founder) of a series of conferences bringing together many of the world's leading researchers in this field of research; to Washington, D.C., for the *Conference on Bluff Body Wakes and Vortex-Induced Vibrations* (3 days - 67 seminars), *BBVIV-1* (1998); to Marseille, France, *BBVIV-2* (2000); to Port Douglas, Australia, *BBVIV-3* (2002); to Santorini, Greece, *BBVIV4* (2005); to Costa do Sauipe, Brazil *BBVIV5* (2007); and finally to Capri Island, Italy for BBVIV6 (2010). Support in the publication of the Proceedings Volumes came from ONR. It is certainly true that much of the recent impetus over the last decade in this field has arisen due to the support from ONR.

During the period of this award, the P.I.'s group has received a number of honours, which are related to the past research conducted under the support of ONR, as follows:

- The P.I. received the Chair: Willis H.Carrier Professor of Engineering in 2009
- The P.I. was a Finalist in *National Science Foundation - International Science & Engineering Visualization Challenge*, in 2009.
- Paper selected Best Article in *Engineering and Computational Mechanics*, in 2009
- Our paper in *Journal of Fluid Mechanics* selected as a "Focus on Fluids" contribution, 2009
- Winner in the *Gallery of fluid motion* 2009 competition, at the American Physical Society meeting. Appeared in *National Geographic, Discovery Channel, New Scientist, Popular Science, American Institute of Physics, NSF*.
- The P.I. was invited to present the *Wallace Prize Lecture* at MIT in 2011.
- The P.I. has been invited to present a Plenary lecture at the *IUTAM Symposium on Unsteady Separated Flows*, Corfu, Greece, June 2007.
- The P.I. has been invited to present a Plenary lecture at the *IUTAM Symposium on Bluff Body Flows*, Kanpur, INDIA. Dec 12-16, 2011
- The P.I. has been invited to present a Review lecture at the *Int. Conference on vortex-induced vibrations*, Trondheim, NORWAY. March 22-23, 2010
- The P.I. has been invited to present a Review lecture at the Conference *RPSEA - Effect of VIV in Oil and Gas Operations*, 11 Jan 2007, Houston, Texas.
- Research student Paolo Luzzatto-Fegiz won the *Acrivos Prize* for the best PhD in Fluid Dynamics nationally. He also won five fellowships in 2011 including one to Woods Hole (where he is presently) and Churchill College, Cambridge (for 2012-2015).
- The P.I. ran the international conference: the *Fifth Bluff Body Wakes and Vortex-Induced Vibrations Conference (BBVIV-5)* held in Costa di Sauipe, Brazil, in Dec 2007
- The P.I. ran the international conference: the *Sixth Bluff Body Wakes and Vortex-Induced Vibrations Conference (BBVIV-6)* held in Capri, Italy in June-July, 2010.

PUBLICATIONS

"VORTEX-INDUCED VIBRATION: UNIVERSAL PHENOMENA IN DIVERSE VIV SYSTEMS"

P.I.   C.H.K.WILLIAMSON

CORNELL UNIVERSITY

Invited REVIEW PAPERS   (Other Journals)

C. H. K. Williamson and R. Govardhan (2008) "A brief review of recent results in vortex-induced vibration", Invited Review in special edition on "Bluff Body Aerodynamics and Applications" *J. Wind Engin. and Industrial Aerodynamics*, **96**, 713-735.

Invited BOOK CHAPTERS:

C. H. K. Williamson (2012) "Flow-Structure Interaction", in *Handbook of Environmental Fluid Dynamics*. (Ed. H.J. Fernando). Taylor & Francis Books Inc.

C. H. K. Williamson (2007) "Bluff Body Aerodynamics", in *Handbook of Experimental Fluid Mechanics*. Springer, Berlin, Heidelberg. Chapter **16.3**, pp. 1125-1146.

SPECIAL EDITOR OF JOURNAL VOLUMES :

T. Leweke & C. H. K. Williamson (2011) Editors of IUTAM Symposium on "Bluff body wakes and vortex-induced vibration", BBVIV6, *Journal of Fluids and Structures*, Volume **27**, 247 pages.

T. Leweke & C. H. K. Williamson (2009) Editors of "Special issue on bluff body wakes and vortex-induced vibration-BBVIV5.", *Journal of Fluids and Structures*, Volume **25**, 170 pages.

REFEREED JOURNAL PAPERS -

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) Structure and stability of the finite-area Karman vortex street. Submitted to *Journal of Fluid Mechanics*.

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) Stability of steady flows and new fluid equilibria from "Imperfect Velocity-Impulse" diagrams. Accepted for *Journal of Fluid Mechanics*.

M. Stremler, A. Salmanzadeh, B. Saikat & C.H.K. Williamson (2011) A mathematical model of 2P and 2C vortex wakes. *Journal of Fluids and Structures*, **27**, 774-783.

T. Leweke and C. H. K. Williamson (2011) "Experiments on Long wave instability in a vortex pair", *Physics of Fluids*, **23**, 024101, 1-14. +FRONT COVER.

A. Mackowski & C. H. K. Williamson (2011) "Developing a Cyber-Physical Fluid Dynamics facility for fluid-structure interaction studies". *Journal of Fluids and Structures*, **27**, 748-757.

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) An accurate and efficient method for computing steady uniform vortices. *Journal of Computational Physics*, **230**, 6495–6511.

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) Resonant instability in two-dimensional vortex arrays. *Proceedings of the Royal Society A*, **467**, 1164–1185.

M. Horowitz & C. H. K. Williamson (2010) "Vortex-induced vibration of a rising and falling cylinder", *Journal of Fluid Mechanics*, **662**, 352-383.

T. Morse & C. H. K. Williamson (2010) "Prediction of steady, unsteady, and transient behaviour in vortex-induced vibration from controlled motion", *Journal of Fluid Mechanics*, **649**, 429-451.

M. Horowitz & C. H. K. Williamson (2010) "The effect of Reynolds number on the dynamics and wakes of freely rising and falling spheres", *Journal of Fluid Mechanics*, **651**, 251-294. + FRONT COVER.

P. Luzzatto-Fegiz & C. H. K. Williamson (2010) "Stability of conservative flows and new steady-fluid solutions from bifurcation diagrams exploiting a variational argument". *Phys. Rev. Lett.*, **104**, 044504.

P. Luzatto Fegiz & C. H. K. Williamson (2010) "Stability of elliptical vortices from "Imperfect Velocity-Impulse" diagrams" *Theoretical and Computational Fluid Dynamics*, **24**, 181- 188.

P. Luzzatto-Fegiz & C. H. K. Williamson (2009) "Stability of steady vortices and new equilibrium flows from "Imperfect-Velocity-Impulse" diagrams". In *Advances in Turbulence XII*, Ed. B. Echardt. *Springer Proceedings in Physics* **132**, 305-308.

T.J. Stallard, P.H. Taylor, C. H. K. Williamson & A.G.L. Borthwick (2009) "Cylinder loading in transient motion representing flow under a wave group", *Proc. Royal Society A*, **465**, 1467-1488.

P. W. Bearman (2009) "Understanding and predicting vortex-induced vibration", *Journal of Fluid Mechanics*, **634**, 1-4. FOCUS ON FLUIDS - Invited Paper written about Morse & Williamson (2009) contribution below.

T. Morse & C. H. K. Williamson (2009) "Prediction of vortex-induced vibration response by employing controlled motion", *Journal of Fluid Mechanics*, **634**, 5-39.
Selected as FOCUS ON FLUIDS paper (Bearman), Volume 634.

T. Morse & C. H. K. Williamson (2009) "The effect of Reynolds number on the critical mass phenomenon in vortex-induced vibration", *Physics of Fluids,* **21**, 045105.

T. Morse & C. H. K. Williamson (2009) "Fluid forces, wake modes, and transitions for a cylinder undergoing controlled oscillations", *Journal of Fluids and Structures*, **25**, 697- 712.

M. Horowitz & C. H. K. Williamson (2008) "Critical mass and a new periodic four-ring vortex wake mode for freely rising and falling spheres", *Physics of Fluids*, **20**, 101701.

T. Morse, R. Govardhan & C. H. K. Williamson (2008) "The effect of end conditions on the vortex-induced vibration of cylinders", *Journal of Fluids and Structures*, **24**, 1227-1239.

INVITED KEYNOTE ADDRESSES AND INVITED PRESENTATIONS:

C. H. K. Williamson (2011) "New Discoveries in Vortex-Induced Vibration"", "Wallace" Prize Lecture, MIT.

C. H. K. Williamson (2011) "Recent research in Vortex-Induced Vibration"",
Plenary Speaker at the *IUTAM Symposium on Bluff Body Flows,* Kanpur, INDIA. Dec 12-16, 2011

C. H. K. Williamson (2011) "Recent research in Vortex-Induced Vibration"",
Plenary Speaker at the *IUTAM Symposium on Bluff Body Flows,* Kanpur, INDIA. Dec 12-16, 2011

C. H. K. Williamson (2010) "Review of Vortex-Induced Vibration"",
Invited Speaker at the *Int. Conference on vortex-induced vibrations,* Trondheim, NORWAY. March 22-23, 2010

C. H. K. Williamson (2007) "Control of vortex dynamics in flow-induced vibration",
Opening Plenary Speaker at the *IUTAM Symposium on Unsteady Separated Flows and their Control*, Corfu, GREECE. April 2007.

C. H. K. Williamson (2007) "Discoveries in Vortex-Induced Vibrations", Invited Seminar *RPSEA - Effect of VIV in Oil and Gas Operations*, 11 Jan 2007, Houston, Texas.

INVITED WEEK SUMMER COURSE -10 hours lectures -(Copenhagen, Denmark) 2010:

- Invited to deliver 10 Hours of lectures on the following area "*Offshore Engineering and Vortex-Induced Vibrations*", Invited Summer Course presented at Technical University of Denmark, Copenhagen.
- Supported by Danish Research Academy. 16-20 August 2010.

CONFERENCE PAPERS

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) *Andreas Acrivos Dissertation Prize Lecture:* Stability of inviscid flows from bifurcation diagrams exploiting a variational argument. *Bulletin of the American Physical Society*, **56**, P27.1.

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) Resonant instability in two-dimensional vortex arrays. *Bulletin of the American Physical Society*, **56**, G21.9.

A. Mackowski & C. H. K. Williamson (2011) "Nonlinear restoring forces in vortex-induced vibration ". *Bull. American Physical Society*, **56**, L21.

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) "Resonant instability in two-dimensional vortex arrays". *Bull. American Physical Society*, **56**, G21.

P. Luzzatto-Fegiz & C. H. K. Williamson (2011) Stability of coherent vortex structures in shear and wake flows. *International Colloquium on "Fundamental Problems of Turbulence: 50 years after the Turbulence Colloquium Marseille 1961"*, 26-30 September, Centre International de Rencontres Mathematiques, Marseille, France.

P. Luzzatto-Fegiz & C. H. K. Williamson (2010) Stability of steady vortices and new equilibrium flows from "Imperfect-Velocity-Impulse" diagrams. *8th Euromech Fluid Mechanics Conference*, 13-16 September, Bad Reichenhall, Germany.

P. Luzzatto-Fegiz & C. H. K. Williamson (2010) "An accurate and efficient method to compute steady uniform vortices". *Bull. American Physical Society*, **55**, GN6.

A. Mackowski & C. H. K. Williamson (2010) " A study of vortex-induced vibration using hybrid cyber-physical supports ". *Bull. American Physical Society*, **55**, HN3.

P. Luzzatto-Fegiz & C. H. K. Williamson (2010) " Stability of steady vortices and new equilibrium flows from "Imperfect-Velocity-Impulse" diagrams.". *8th European Fluid Mechanics Conference,* Bad Reichenhall, GERMANY, 13-16 Sept 2010.

P. Luzzatto-Fegiz & C. H. K. Williamson (2010) "Determining the structure and stability of steady wake flows using "IVI diagrams"". *Proc. 6th (IUTAM) Symp. on Bluff Body Wakes and Vortex-Induced Vibrations BBVIV6*, Capri Island, ITALY, 22-25 June 2010.

A. Mackowski & C. H. K. Williamson (2010) "Developing a Cyber-Physical Fluid Dynamics facility for fluid-structure interaction studies". *Proc. 6th (IUTAM) Symp. on Bluff Body Wakes and Vortex-Induced Vibrations BBVIV6*, Capri Island, ITALY, 22-25 June 2010.

P. Luzzatto-Fegiz & C. H. K. Williamson (2009) " Stability of steady vortices and new equilibrium flows from "Imperfect-Velocity-Impulse" diagrams". *12th European Turbulence Conference,* Marburg, Germany, 7-10 Sept 2009.

P. Luzzatto-Fegiz & C. H. K. Williamson (2009) "Deriving Kelvin's argument through the principle of 'virtual vortex work'". *Bull. American Physical Society*, **54**, BT1.

A. Mackowski & C. H. K. Williamson (2009) "Using a hybrid cyber-physical system in the study of body motion due to vortex dynamics". *Bull. American Physical Society*, **54**, AT8.

C. H. K. Williamson (2008) "Trailing vortex pairs in ground effect". Paper for *Int. Conf. on Fundamental issues related to aircraft trailing wakes*, Marseille, FRANCE, 27-29 May 2008.

P. Luzatto Fegiz & C. H. K. Williamson (2008) "Stability of steady inviscid flows from "Imperfect Velocity-Impulse" diagrams" Proc. *IUTAM Symposium 150 Years of Vortex Dynamics*, TU Denmark, Lyngby, DENMARK, 12-16 Oct 2008.

C. H. K. Williamson & P. Luzatto Fegiz (2008) "Stability of classical flows and new vortical solutions from preferred bifurcation diagrams". *IUTAM Symposium 150 Years of Vortex Dynamics*, TU Denmark, Lyngby, DENMARK, 12-16 Oct 2008.

M. Horowitz & C. H. K. Williamson (2008) "Critical mass and new wake patterns for freely rising and falling spheres". Paper for *9th Int. Conf. on Flow-Induced Vibrations (FIV 2008)*, Prague, CZECH REPUBLIC, 30 June – 3 July 2008.

T. L. Morse & C. H. K. Williamson (2008) "Understanding mode transitions in vortex-induced vibration using controlled vibration". Paper for *9th Int. Conf. on Flow-Induced Vibrations (FIV 2008)*, Prague, CZECH REPUBLIC, 30 June – 3 July 2008.

M. Horowitz & C. H. K. Williamson (2008) "The effect of Reynolds number on the dynamics of freely rising and falling spheres". *Bull. American Physical Society*, **53**, EP5.

P. Luzatto Fegiz & C. H. K. Williamson (2008) "Determining the stability of steady inviscid flows through "Imperfect Velocity-Impulse" diagrams". *Bull. American Physical Society*, **53**, AU5.

P. Luzatto Fegiz & C. H. K. Williamson (2007) "Stability and evolution of a family of $M = 2$ uniform vortices". *Third European SCAT Workshop: Vortices and Vortex Sheets: Theories, Numerics and Applications*, Porquerolles, FRANCE, 4-10 June 2007.

M. Horowitz & C. H. K. Williamson (2007) "Dynamics and wake patterns of rising and falling spheres". *Proc. 5th Conf. on Bluff Body Wakes and Vortex-Induced Vibrations BBVIV5*, Costa do Sauípe, BRAZIL, 12-15 Dec. 2007.

T. L. Morse & C. H. K. Williamson (2007) "Understanding mode transitions in vortex-induced vibration using controlled vibration". *Proc. 5th Conf. on Bluff Body Wakes and Vortex-Induced Vibrations BBVIV5*, Costa do Sauípe, BRAZIL, 12-15 Dec. 2007.

M. Horowitz & C. H. K. Williamson (2007) "Dynamics and wake patterns of freely rising and falling spheres at Re = 500". *Bull. American Physical Society*, **52**, Gallery of Fluid Motion.

M. Horowitz & C. H. K. Williamson (2007) "Evolution of wake vorticity structures causing vibration of freely rising spheres". *Bull. American Physical Society*, **52**, KT1.

P. Luzatto Fegiz & C. H. K. Williamson (2007) "The Stability and Evolution of a Family of M = 2 Uniform Vortices". *Bull. American Physical Society*, **52**, ER8, 108.

T. L. Morse & C. H. K. Williamson (2007) "An investigation of wake mode transitions and amplitude jumps in vortex-induced vibration using controlled vibration". *Bull. American Physical Society*, **52**, KT2.